LBL-39030
UCB-PTH-96/28

Excluding Light Gluinos from Z decays*

André de Gouvêa and Hitoshi Murayama

Department of Physics, University of California
Berkeley, California 94720
and
Theoretical Physics Group
Ernest Orlando Lawrence Berkeley National Laboratory
University of California, Berkeley, California 94720

Abstract

We reanalyze the constraints on light gluinos ($m_{\tilde{g}} \leq 5$ GeV/c^2) from the hadronic Z decays into four jets. We find that the published OPAL data from the 1991 and 1992 runs exclude a light quasi-stable gluino with mass $\lesssim 1.5$ GeV/c^2 at more than 90% confidence level. This limit depends little on assumptions about the gluino fragmentation and the definition of the gluino mass. The exclusion confidence level is shown as a function of the mass. A future projection is briefly discussed. We also discuss quantitatively how the distributions in the Bengtsson–Zerwas and the modified Nachtmann–Reiter angles change due to the finite bottom quark or gluino mass. The analysis is limited to the leading-order calculations. We, however, give an empirical reason to why the next-to-leading-order corrections are unlikely to change our conclusions.

*AdG was supported by CNPq (Brazil). HM was supported in part by the Director, Office of Energy Research, Office of High Energy and Nuclear Physics, Division of High Energy Physics of the U.S. Department of Energy under Contract DE-AC03-76SF00098 and in part by the National Science Foundation under grant PHY-95-14797.

Supersymmetry is one of the primary targets of extensive searches at various collider experiments, most importantly at CERN e^+e^- collider LEP and Fermilab $p\bar{p}$ collider Tevatron [1]. Negative searches at these and previous colliders have already put significant constraints on the parameter space of low-energy supersymmetry. However, a light gluino below the few GeV mass range has surprisingly weak experimental constraints as emphasized recently by various authors [2, 3, 4] (see, however, an opposing view [5]). It is an extremely important task to verify or exclude a gluino in this light window experimentally. While the Tevatron Run II is expected to extend the reach of heavy gluinos up to a few hundred GeV, little effort is devoted to definitively exclude or verify the light gluino window. On the other hand, a careful reexamination of the existent data may reveal an overlooked constraint on a light gluino; this is our motivation to study the existent data in detail.

We reanalyzed published data on Z decays into four jets [6, 7, 8, 9, 10, 11], and found that they already exclude a gluino lighter than 1.5 GeV/c^2 at more than 90% confidence level. We assume that the gluino does not decay inside the detector. Since the published results use only 1991 and 1992 data, it is conceivable that the currently available data, if analyzed properly, could put a much more significant constraint on a light gluino. We hope our result urges the experimental groups to analyze the whole data set including a possible light gluino.

Let us briefly review the existent constraints on a light gluino (see [3, 12] for more details). The negative searches at beam dump experiments have excluded a light gluino which decays inside the detector into photino, which in turn interacts with the neutrino detector. However, a gluino tends to leave the detector without decaying if the squark mass is above a few hundred GeV/c^2 [13, 14]. Even if the gluino decays, the photino interacts very weakly in this case and cannot be detected. If the gluino does not decay, it forms bound states such as gluinoball $\tilde{g}\tilde{g}$, glueballino $g\tilde{g}$ or baryon-like states, especially $uds\tilde{g}$ [15]. Other states are likely to decay into these neutral bound states, and searches for exotic charged hadrons may not apply unless a charged gluino bound state decays only weakly. One the other hand, the mass region above 1.5 GeV/c^2 and below 4 GeV/c^2 is excluded from quarkonium decay $\Upsilon \to \gamma\eta_{\tilde{g}}$, where $\eta_{\tilde{g}}$ is the pseudo-scalar gluinoball, independent of the gluino lifetime [16, 3]. Whether the bound extends to lower masses is controversial because of the applicability of perturbative QCD calculations [16]. The mass range above 4 GeV/c^2 is expected to give a shorter lifetime

and is excluded by a negative search for events with missing energy at UA1 [17]. The authors of [18] claim that the limit from UA1 extends down to 3 GeV/c^2. In any case, the least constrained region is the mass range below 1.5 GeV/c^2, where the gluino is relatively stable so that it does not decay inside detectors. This is our window of interest in this letter.

We would like to emphasize that the best method to exclude the gluino mass range below 1.5 GeV/c^2 is to use inclusive processes rather than searching for specific bound states with certain decay modes. The latter search would heavily depend on assumptions such as the mass spectrum of various gluino bound states and their decay modes and decay lifetimes. One would have to design experiments and put constraints with all possible theoretical assumptions on gluino bound states in order to exclude the light gluino definitively. On the other hand, the constraints would be much less sensitive to theoretical assumptions if they were based on inclusive processes where perturbative QCD is applicable. There are several possibilities pointed out in the literature along this line. The most popular one is to study the effect of light gluinos in the running of the QCD coupling constant α_s. It was even pointed out that the values of α_s from higher energy measurements tend to be higher than those extrapolated from lower energies using QCD with the ordinary quark flavors, and the data actually prefer the existence of a light gluino to compensate the slight discrepancy [2, 19, 20]. However, this issue remains controversial [21, 22, 23]. Even though the discrepancy between low-energy and high-energy measurements is diminishing [24], still the data are not precise enough to exclude or verify a light gluino definitively. The second one is its effect on the Altarelli–Parisi evolution of the nucleon structure functions [25, 26]. Unfortunately the effect is too small to be tested using the present experimental data. It might be that the more recent HERA data could improve the situation, but making a definite statement on the existence of a light gluino appears to be difficult. The third one is to study the angular correlations in the so-called "3+1" jet events at HERA [27]. However, the effect of the light gluino was found to be negligible. The final one, which we employ in this letter, is the study of four jet correlations in e^+e^- collisions [28, 23, 29]. Previous studies did not find significant constraints, but given the size of the current LEP data, we find this to be the most promising direction.

The only data we use in this letter are studies of QCD color factors [9, 10, 11]. The experimental groups at LEP have performed impressive

analyses of the hadronic Z decays into four jets, extracting QCD color factors C_A/C_F and T_F/C_F [30] from jet angular distributions, to confirm SU(3) as the QCD gauge group and five light quark flavors. The angular distributions of $q\bar{q}q\bar{q}$ final state differ from those of $q\bar{q}gg$, where q refers to a generic quark and g to a gluon. Three angles are commonly used in four-jet analyses: the Bengtsson–Zerwas (BZ) angle χ_{BZ} [31], the modified Nachtmann–Reiter (NR) angle θ^*_{NR} [32], and the opening angle of the two less energetic jets α_{34}. If there exists a light gluino $\tilde{g}$, the final state $q\bar{q}\tilde{g}\tilde{g}$ also contributes to the Z decays into four jets. The angular distributions of $q\bar{q}\tilde{g}\tilde{g}$ would be identical to those of $q\bar{q}q\bar{q}$. Therefore, a possible light gluino would change the extracted T_F/C_F but not C_A/C_F. Apart from the mass effects, T_F/C_F should increase by a factor of $(5+3)/5$, because the gluino is a color-octet and counts effectively as three additional massless quarks. Note that these analyses do not use the overall rate of four-jet events since it is sensitive to the choice of α_s in the absence of next-to-leading order (NLO) calculations. So far the experimental analysis which used the highest statistics is the one by OPAL [11], which also briefly discussed constraints on a light gluino. They found that the light gluino is barely outside the 68% confidence level contour and decided the data did not put a significant constraint.

However, we find the previous analyses not carefully designed to study the effect of a light gluino because of the following reason. When one discusses a possible light gluino, QCD with the color group SU(3) should be assumed. Given overwhelming experimental evidences of QCD, it is not wise to, for instance, vary the number of colors $N_c = 3$ when one studies the effect of a particle (light gluino) *added to* QCD. Therefore, we must fix the QCD color factor C_A/C_F to be that of the SU(3) group, 9/4. Second, we already *know* that there are five quark flavors u, d, s, c and b, which appear in Z hadronic decays. When one puts constraints on an *additional* contribution from a light gluino, one should not vary the number of flavors below 5, or equivalently, T_F/C_F below 3/8. The only LEP paper which analyzed data in a way close to this spirit, and put an upper bound on possible additional $q\bar{q}q\bar{q}$-type final states, is the one from OPAL [7]; but it used very limited statistics. All more recent papers [9, 10, 11] varied both C_A/C_F and T_F/C_F without constraints. By reanalyzing data with these constraints we can put a much more significant bound on a light gluino than reported. Actually, fixing the group to be SU(3) ($C_A/C_F = 9/4$) has the greatest impact on the confidence level, while restricting $T_F/C_F \geq 3/8$ has a much smaller effect

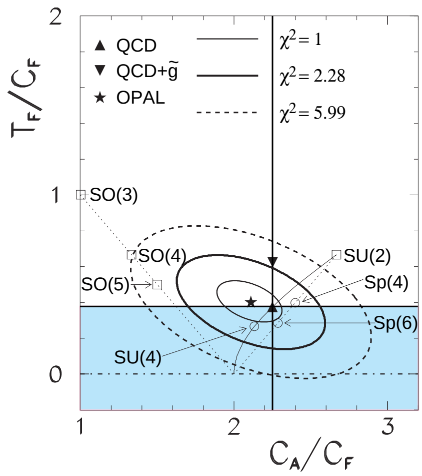

Figure 1: Extracted QCD color factors from the OPAL analysis [11]. The shown χ^2 values correspond to 39.3%, 68% and 95% confidence levels with two degrees of freedom. We impose the constraint $C_A/C_F = 9/4$ (vertical solid line) and limit ourselves to the unshaded region ($T_F/C_F \geq 3/8$) in order to put constraints on a possible light gluino contribution to the four-jet events from Z decays. See the text for more details.

(actually it makes the significance worse). We further include the finite mass of the bottom quark in the analysis which slightly improves the significance. Overall, a massless gluino is excluded already better than at 90% confidence level by the OPAL 1991 and 1992 data only [11].

Let us start from the reported contour on the C_A/C_F, T_F/C_F plane, shown in Fig. 1. We fix $C_A/C_F = 9/4$ because of the philosophy of our study stated above. Since one-dimensional χ^2 distributions have much higher confidence levels than two-dimensional ones, this change improves the significance of the data drastically. From their χ^2 contours, we minimized χ^2 with fixed $C_A/C_F = 9/4$, and defined $\Delta\chi^2$ relative to the χ^2 at the minimum ($T_F/C_F = 0.36$). The confidence levels are calculated using a one-dimensional χ^2 distribution with $\Delta\chi^2$ defined in this manner. This is a conservative choice because $\Delta\chi^2 < \chi^2$. We obtain $T_F/C_F = 0.36 \pm 0.15$ with fixed C_A/C_F. If one had used this central value and the standard deviation, a massless gluino would be excluded at 95% confidence level. However, we also need to impose another constraint, $T_F/C_F \geq 3/8$, which can be easily

taken into account. The standard method is to use the Gaussian distribution only in the physical region, and scale the normalization of the distribution so that the total probability in the physical region becomes unity. Since the central value is very close to the theoretical value of the QCD, this effectively increases the probability of allowing light gluinos by a factor of two; numerically the confidence level is 88%.

Finally, we study the effect of the finite mass of the bottom quark and gluinos on the extracted T_F/C_F. The authors of [33] studied the effect of the finite mass of quarks on the four-jet rates. They also looked at the angular distributions and reported there were little changes. Even though it is true that the distributions do not change drastically, they gradually become similar to those of $q\bar{q}gg$ final state as one increases the mass of the quark, and hence the extracted T_F/C_F from the fit to the distributions has a relatively large effect due to the finite mass of the bottom quark. The papers [9, 10] do not take this effect into account at all. The OPAL experiment [11] used parton level event generators by the authors of [33] and [29] to study the effect. They have found a surprisingly large effect: the bottom quark contribution to T_F/C_F was about one half of a massless quark at $y_{cut} = 0.03$. We confirmed their estimate in a detailed parton-level calculation based on that done in [34], neglecting the interference between primary and secondary quarks. This approximation is known to be better than a few percent. On the other hand, this approximation has the clear advantage of enabling us to distinguish primary and secondary quarks unambiguously. Our code employs helicity amplitude technique using the HELAS package [35], which made it straight-forward to incorporate finite masses in the four-jet distributions.

The finite mass affects the extracted T_F/C_F in two ways. First, the rate of producing secondary massive quarks is suppressed compared to the massless case as shown with the solid line in Fig. 2. For instance, there is about 20% suppression with $m_q = 5$ GeV$/c^2$ and $y_{cut} = 0.03$. This result is consistent with [33]. The mass of the primary quark has little effect on the rate: only a 6% suppression for $m_q = 5$ GeV$/c^2$. We also checked that the distributions in BZ and NR angles with a massive primary quark are indistinguishable from the massless case. These observations are consistent with naive expectations, because the primary quarks are much more energetic than the secondary ones and hence the mass effect is suppressed by m^2/E^2. We therefore neglect the finite mass of primary quarks hereafter. Second, the NR and BZ angle distributions gradually approach those of the $q\bar{q}gg$ final state as one increases

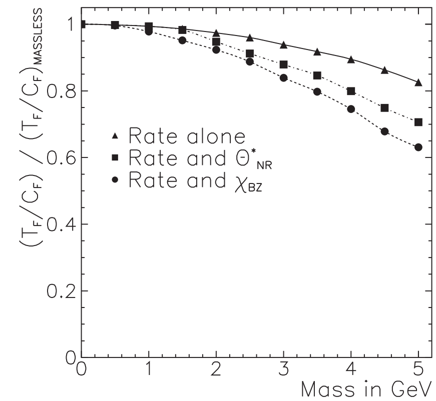

Figure 2: Effective contribution to T_F/C_F of a massive secondary quark relative to the massless case. The solid line shows the reduction in the rate alone. The other two lines include the effect that the distributions in BZ and NR angles change due to finite quark mass. We chose $y_{cut} = 0.03$ and $\sqrt{s} = m_Z c^2 = 91.17$ GeV.

the mass of the secondary quarks. We are not aware of detailed analyses of these distributions with massive quarks in the literature. The distributions are shown in Fig. 3 normalized so that the total area below the curve is unity, in order for the effect on the rate and that on the distribution to be clearly separated. We fit the distributions as linear combinations of $q\bar{q}gg$ and massless $q\bar{q}q\bar{q}$ distributions to determine the *effective* T_F/C_F, in order to mimic the experimental analyses. The fit is surprisingly good; we checked this for quark masses between 0 and 5 GeV/c^2. Combined with the reduction in the rate, the net effect of the finite mass of secondary quarks is shown in Fig. 2. With $m_b = 5$ GeV/c^2 for secondary bottom quarks, the overall rate of $q\bar{q}b\bar{b}$ final state is reduced to 82.5%, while the fit to angular distributions gives a T_F/C_F reduced to 76.4% (BZ) or 85.5% (NR) compared to that of a massless quark flavor (3/8), on top of the reduction in the rate. In total, secondary bottom quarks contribute to T_F/C_F as $3/8 * 0.630$ or $3/8 * 0.705$, which is not a negligible suppression. The extracted T_F/C_F from the data is an average of T_F/C_F from five flavors. The reported T_F/C_F in [11] includes a correction to compensate the apparent suppression due to the finite bottom quark mass. Such a correction in turn effectively enhances the additional contribution from gluinos by a factor of $5/(4 + 0.630)$ or $5/(4 + 0.705)$. Note

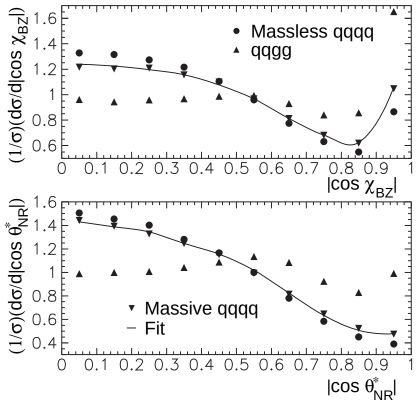

Figure 3: The distributions in BZ and NR angles of the $q\bar{q}q\bar{q}$ final state where the secondary quark has a mass of 5 GeV$/c^2$. They can be fit extremely well as a linear combination of massless $q\bar{q}q\bar{q}$ and $q\bar{q}gg$ distributions. We used $y_{cut} = 0.03$ and $\sqrt{s} = m_Z c^2$.

that this slight enhancement effect does not change significantly even when one varies m_b from 4 to 5 GeV$/c^2$, as can be seen in Fig. 2.

The actual OPAL analysis [11] fits the data in the three dimensional space spanned by BZ, NR and α_{34} angles after bin-by-bin systematic corrections from Monte Carlo simulations. Such an analysis is beyond the scope of this letter. We assume that the total effect of the finite mass is somewhere between the effects on BZ or NR angles since α_{34} is not as effective in extracting T_F/C_F. As it is clear from Fig. 3, fits to distributions of massive quarks give apparent additional contributions to $q\bar{q}gg$ and hence C_A/C_F. They are completely negligible, however, compared to the size of the true $q\bar{q}gg$ which is about one order of magnitude larger than the sum of all $q\bar{q}q\bar{q}$ final states, and hence we will neglect such contributions hereafter.

Given the above considerations, we can now present the exclusion confidence levels on a light gluino for varying gluino masses in Fig. 4. For both curves, we used $m_b = 5$ GeV$/c^2$ and used the effective T_F/C_F extracted from the fits to BZ and NR angles. The finite mass effect of the gluino is treated in the same manner. First of all, it is clear that the finite mass effect which we studied depends little on the choice of BZ or NR angles, and hence we believe it mimics the true experimental fits (which use BZ, NR and α_{34} angles simultaneously in a three-dimensional fit with 295 bins) quite well. Second,

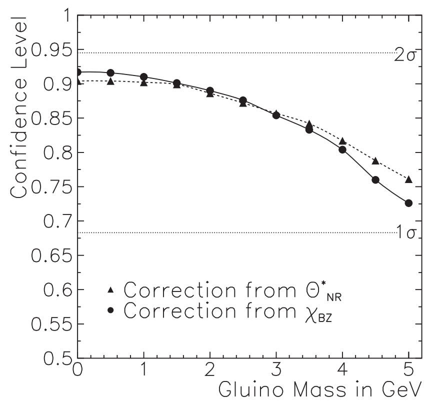

Figure 4: Exclusion confidence level of a light gluino as a function of its mass. Two curves are shown depending on the method of estimating the finite mass effects. In either case, a light gluino of mass below 1.5 GeV/c^2 is excluded at more than 90% confidence level.

the confidence level is extremely flat up to 2 GeV/c^2. This implies that we do not need to worry about complication due to non-perturbative dynamics in defining the gluino mass [36]. The lower bound of $\simeq$ 1.5 GeV/c^2 at 90% confidence level is already in the perturbative region. It is quite likely that the gluino mass relevant to this analysis is a running mass defined at the scale $Q^2 \sim y_{cut} m_Z^2$ [37]. It is then straight-forward to convert the bound to the on-shell gluino mass: the lower bound of $\bar{m}_{\tilde{g}}(0.03 m_Z^2) = 1.5$ GeV/c^2 in the $\overline{\mathrm{MS}}$ scheme corresponds to $m_{pole}(\tilde{g}) = 2.8$ GeV/c^2.

We would like to comment that the clever jet reconstruction method used in the OPAL analysis [11] is particularly suited for the study of light gluinos in four-jet events. They did not scale the measured jet energies by an overall ratio E_{vis}/m_Z, as done traditionally in similar analyses, but instead used the angular information of the jets to calculate the energy of each jet using energy and momentum conservation. This method avoids uncertainties in the gluino fragmentation. Since it is not well understood how a gluino fragments, one should use a similar method to avoid dependence on assumptions about the gluino fragmentation in future studies.

Unfortunately, our analysis is limited to the leading-order (LO) calculations. It is a natural question whether the NLO corrections may change our conclusion. First of all, we expect that the corrections to the angular vari-

ables used in the analysis are presumably not large. The NLO corrections are important when a variable involves α_s, such as 3- and 4-jet rates, thrust, etc. The variables used in our analysis are not proportional to powers of α_s, and hence scale-independent at the LO approximations. This is analogous to the case of the forward-backward asymmetry which is an (integrated) angular variable and is α_s independent at the LO. It does receive an NLO correction of $c(\alpha_s/\pi)$, where $c \sim 0.89$ in the case of a massless quark [38]. In our case, we also expect a correction to the angular distributions of the order of $\alpha_s(\mu)/\pi$, where $\mu^2 \sim y_{cut} m_Z^2$ is probably an educated guess. Then a typical size of the NLO correction is about 5 %. However, a correction of this order of magnitude may still be of concern because of the following reason. The $q\bar{q}gg$ final state is roughly an order of magnitude larger than the $q\bar{q}q\bar{q}$ final state. Therefore, a 5% correction to $q\bar{q}gg$ may result in a 50% correction to $q\bar{q}q\bar{q}$ final state, to be compared with a possible 60 % contribution from the gluino.

We argue, however, that such a higher order correction is not likely to change our conclusion. First of all, the helicity structure and the color flow in the $q\bar{q}gg$ final state and $q\bar{q}q\bar{q}$ final state are quite different. If a correction to the $q\bar{q}gg$ final state changes the conclusion, the following must be happening: the correction term to the $q\bar{q}gg$ exactly mimics an additional contribution to the $q\bar{q}q\bar{q}$ final state in the angular distributions with a negative sign such as to mask the contribution from the $q\bar{q}\tilde{g}\tilde{g}$ final state. We do not find this to be likely because they have different structures in the helicities and colors. Moreover, the data do not indicate that the NLO correction is large. OPAL data [11] are fit very well by the LO Monte Carlo on three-dimensional histograms of 295 bins with $\chi^2/\text{d.o.f} = 290/292$. This excellent agreement between the matrix element calculation and the data found in [11] supports the smallness of the NLO corrections empirically. However, the calculations of NLO corrections are necessary to justify it.[2] For future studies, it is also desirable to compare different Monte Carlo programs, while only JETSET was used in recent experimental papers [9, 10, 11].

Finally, it is worth emphasizing that the result in this letter is based on the 1991 and 1992 OPAL data with 1.1M hadronic Z's [11]. The statistical

[2]It is encouraging that partial NLO calculations were done after the completion of this work [39]. A preliminary study shows that the correction from leading terms in $1/N_c^2$ expansion is small [40].

and systematic uncertainties are comparable in their paper. Given the current size of the LEP data, which is more than an order of magnitude larger, the statistical uncertainty should reduce substantially once all of the data has been analyzed. This change alone could drastically improve the sensitivity to the light gluino in four-jet events. On the other hand, it is not obvious how systematic uncertainties can be further reduced. The largest systematic uncertainty originates in the bin-by-bin acceptance corrections which needed to be done before performing a fit in BZ, NR, and the opening angle space. It is not clear how this uncertainty can be reduced if one employs the same method. Perhaps choosing larger values of y_{cut} reduces the uncertainty while reducing the statistics at the same time. There could be an optimal choice of y_{cut} for this particular purpose. Some of the other large systematic uncertainties are specific to the OPAL experiment and could be reduced by averaging results from all four experiments. In any case, there is no doubt that we can expect a better result from the currently available data set.

In summary, we reanalyzed the published OPAL 1991 and 1992 data on the QCD color factors [11] to constrain possible additional contributions to four-jet events in Z decays due to $q\bar{q}\tilde{g}\tilde{g}$ final states. The main difference from the original OPAL study is to fix $C_A/C_F = 9/4$ as required by QCD. We further imposed $T_F/C_F \geq 3/8$ and treated the finite mass effects of both the bottom quark and the gluino carefully. We find that a light gluino with a mass below 1.5 GeV/c^2 is excluded at better than 90% confidence level. The result is insensitive to assumptions about what bound state it forms, the definition of its mass, and the gluino fragmentation provided that it does not decay inside the detectors. We believe that the currently available data set is much more sensitive to a possible additional contribution from the light gluino.[3] We argued that the NLO corrections are unlikely to modify the conclusion; still, this assertion needs to be justified by explicit calculations in the future. As a by-product of this analysis, we discussed the effect of finite bottom quark mass on BZ and NR distributions in detail, which is not negligible when extracting QCD color factors at current precisions.

[3] A paper by ALEPH [41] came out after the completion of this work, which claims to exclude a light gluino below 6.3 GeV by combining the four-jet angular variables with the two-jet rate. This type of analysis may be more sensitive to the NLO corrections.

Acknowledgments

HM thanks Mike Barnett, John Ellis, Lance Dixon, Ian Hinchliffe, and Kam-Biu Luk for useful conversations. We thank Axel Kwiatkowski for comments on the manuscript. AdG was supported by CNPq (Brazil), and HM was supported in part by the Director, Office of Energy Research, Office of High Energy and Nuclear Physics, Division of High Energy Physics of the U.S. Department of Energy under Contract DE-AC03-76SF00098 and in part by the National Science Foundation under grant PHY-95-14797.

References

[1] For a recent review, see H. Baer *et al.*, LBL preprint LBL-37016, hep-ph/9503479, to appear in "Electroweak Symmetry Breaking and Beyond the Standard Model," eds. T. Barklow, S. Dawson, H. Haber, and J. Siegrist, World Scientific.

[2] L. Clavelli, *Phys. Rev.* **D46**, 2112 (1992).

[3] G. R. Farrar, *Phys. Rev.* **D51**, 3904 (1995).

[4] R. M. Barnett, in Proceedings of "Beyond the Standard Model IV," eds. J. F. Gunion, T. Han, and J. Ohnemus, World Scientific, 1995.

[5] H. E. Haber, in Proceedings of the International Workshop on Supersymmetry and Unification of Fundamental Interactions (SUSY 93), ed. Pran Nath, World Scientific, 1993.

[6] B. Adeva *et al.*, *Phys. Lett.* **B 248**, 227 (1990).

[7] M. Z. Akrawy *et al.*, *Z. Phys.* **C 49**, 49 (1991).

[8] P. Abreu *et al.*, *Phys. Lett.* **B255**, 466 (1991).

[9] D. Decamp *et al.*, *Phys. Lett.* **B284**, 151 (1992).

[10] P. Abreu *et al.*, *Z. Phys* **C59**, 357 (1993).

[11] R. Akers *et al.*, *Z. Phys.* **C65**, 367 (1995).

[12] R. M. Barnett *et al.*, to appear in *Phys. Rev.* **D 54**, 1 (1996).

[13] G. R. Farrar, *Phys. Rev. Lett.*, **53**, 1029 (1984).

[14] S. Dawson *et al.*, *Phys. Rev.*, **D31**, 1581 (1985).

[15] F. Bucella, G. R. Farrar, and A. Pugliese, *Phys. Lett.*, **B153**, 311 (1985).

[16] M. Çakir and G. R. Farrar, *Phys. Rev.* **D 50**, 3268 (1994).

[17] C. Albajar *et al.*, *Phys. Lett.* **198B**, 261 (1987).

[18] R. M. Barnett, H. E. Haber, and G.L. Kane, *Nucl. Phys.* **B267**, 625 (1986).

[19] L. Clavelli, P.W. Coulter, and K.-j. Yuan, *Phys. Rev.* **D47**, 1973 (1993).

[20] L. Clavelli, and P.W. Coulter, *Phys. Rev.* **D51**, 1117 (1995).

[21] I. Antoniadis, J. Ellis, and D. V. Nanopoulos, *Phys. Lett.* **B262**, 109 (1991).

[22] T. Hebbeker, *Z. Phys.* **C60**, 63 (1993).

[23] J. Ellis, D.V. Nanopoulos, and D. A. Ross, *Phys. Lett.* **B305**, 375 (1993).

[24] For instance, see I. Hinchliffe in [12].

[25] R.G. Roberts and W.J. Stirling, *Phys. Lett.* **B313**, 453 (1993).

[26] J. Blümlein and J. Botts, *Phys. Lett.* **B325**, 190 (1994); Erratum, *ibid.*, **B331**, 450 (1994).

[27] R. Muñoz-Tapia and W.J. Stirling, *Phys. Rev.* **D52**, 3984 (1995).

[28] G. R. Farrar, *Phys. Lett.* **B265**, 395 (1991).

[29] R. Muñoz-Tapia and W.J. Stirling, *Phys. Rev.* **D49**, 3763 (1994).

[30] The QCD color factors are defined by $C_F\mathbf{1} = \sum_a T^aT^a$ and $T_F\delta^{ab} = \mathrm{Tr}(T^aT^b)$ for the fundamental representation, and $C_A\delta^{ab} = \mathrm{Tr}(T^aT^b)$ for the adjoint representation. T^a $(a = 1, \ldots, 8)$ are group generators in each representations.

[31] M. Bengtsson and P.M. Zerwas, *Phys. Lett.* **208B**, 306 (1988).

[32] O. Nachtmann and A. Reiter, *Z. Phys.* **C16**, 45 (1982); M. Bengtsson, *Z. Phys.* **C42**, 75 (1989).

[33] A. Ballestrero, E. Maina, and S. Moretti, *Phys. Lett.* **B294**, 425 (1992); *Nucl. Phys.* **B415**, 265 (1994).

[34] C. D. Carone and H. Murayama, *Phys. Rev. Lett.* **74**, 3122 (1995).

[35] H. Murayama, I. Watanabe, and K. Hagiwara, KEK-91-11, Jan 1992.

[36] There are several possible definitions of gluino mass which may appear in experimental constraints: the mass of glueballino $m(R^0)$, the constituent mass $m_{const}(\tilde{g})$, the $\overline{\rm MS}$ current mass $\bar{m}_{\tilde{g}}(\bar{m}_{\tilde{g}})$, the on-shell (pole) mass $m_{pole}(\tilde{g})$, and one half the mass of the pseudo-scalar gluinoball $m(\eta_{\tilde{g}})/2$. The various definitions are not expected to differ much from each other if $m_{\tilde{g}} \gtrsim 2$ GeV/c^2. One may worry about this ambiguity for smaller gluino masses, but our result is insensitive to it since the confidence level in Fig. 4 is extremely flat up to 2 GeV/c^2.

[37] We thank J. Ellis for discussions on this point.

[38] A. Djouadi, B. Lampe, and P. M. Zerwas, *Z. Phys.* **C67**, 123 (1995).

[39] A. Signer and L. Dixon, *Phys. Rev. Lett.* **78** 811 (1997);
E.W.N. Glover, and D.J. Miller, DTP-96-66, hep-ph/9609474;
Z. Bern, L. Dixon, D. A. Kosower, and S. Weinzierl, SLAC-PUB-7316, hep-ph/9610370.

[40] L. Dixon, private communication.

[41] R. Barate *et al.*, CERN-PPE-97-002.